CONSTRAINTS ON MARS' CRUSTAL AND LITHOSPHERIC PROPERTIES FROM MARS GLOBAL SURVEYOR DATA

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We used comparisons of gravity and geoid with topography in the spatial and spectral domains, together with additional information from the geologic record, to constrain support mechanisms for loads on the surface of Mars and their implications for the planet's crustal and lithospheric properties and evolution. The comparisons were carried out using the latest spherical harmonic models of gravity (Yuan et al., 2000) and topography (Smith et al., 1999) derived from Mars Global Surveyor (MGS) data. From gravity-topography correlations we find that a significant portion of the surface of Mars is substantially isostatically compensated. The Tharsis structure is only weakly compensated and seems supported essentially by a combination of flexural and membrane stresses. Basins with large "mascon" gravity highs (e.g., Utopia) are overcompensated, whereas the low gravity anomalies associated with the Hellas basin imply a large degree of compensation. Using spatial domain, Geoid-Topography Ratio (GTR) techniques (Kucinskas and Turcotte, 1994) we find that, with the exception of Tharsis and the large mascon anomaly basins, Airy isostasy is a viable compensation model with a mean, global crustal thickness C of about 100 km. Such a thick crust is in good agreement with predictions of models of the Martian interior based on the geochemistry of SNC meteorites (Spohn et al., 1998). Given our estimate of C, a spectral domain comparison of the ratio of observed geopotential to topography to theoretical ratios (Turcotte et al., 1981) yields a mean, global elastic lithosphere thickness L of about 135 km. Then, given our estimates of C and L, we compared stresses calculated using a planetary thin-shell formulation (Banerdt, 1986) to stress directions inferred from observed tectonic features. We conclude that the thick, present-day Martian crust and lithosphere indicated by this study is mechanically consistent with the observed geology of Mars. Without crustal recycling, magmatism could have created a thick crust early in Mars' evolution, with a substantial fraction of radiogenic heat-producing elements (HPE) fractionated into the crust, resulting in a cool, highly differenciated interior, an increase in lithosphere thickness, and the decay of tectonic and volcanic activity. Assuming that the concentration (and heat generation) of crustal HPE on Mars decreases exponentially with depth, as is the case for continents on Earth (Turcotte and Schubert, 1982), results in a colder, high viscosity lower crust which could be maintained against relaxation for a significant part of Martian history.

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I. OBJECTIVES

Comparisons of gravity and geoid with topography in the spatial and spectral domains are used, together with additional information from the geologic record, to constrain support mechanisms for loads on the surface of Mars and their implications for the planet's crustal and lithosperic properties (namely, strength and mean thickness) and evolution.

Using Mars Global Surveyor (MGS) data derived gravity and topography spherical harmonic models, along with spatial domain Geoid-Topography Ratio (GTR) techniques, we first test Airy isostasy on Mars and obtain a mean, reference crustal thickness C for areas on the planet where Airy compensation is physically plausible. Based on our estimate of C, a spectral domain comparison of the ratio of observed geopotential to topography to theoretical ratios yields a mean, global elastic lithosphere thickness L. Then, to address the non-uniqueness problem in geophysical modeling studies based on gravity and topography alone, and to examine the mechanical validity of our estimates of C and L with respect to the geologic record of Mars, we compare stresses calculated using a planetary thin-shell formulation to stress directions inferred from tectonic features identified in surface imaging data. Inferences on Mars' geodynamic evolution follow.

II. MARS DATA

Constraints on our crustal and lithospheric models are provided by two main categories of Mars data: 1) the latest, high resolution spherical harmonic expansions of planetary gravity/geoid (equipotential surface) and topography, and 2) global maps for different types of tectonic features derived from Viking and MGS (MOC) images, taken from the litterature.

O Mars topography model: we use a 70 th degree and order spherical harmonic model derived from the MOLA data (Smith et al., 1999a). The model is illustrated in Figure 1. Topography values in this map are with respect to the reference ellipsoid defined below.

The global physiography of Mars is dominated essentially by two features: 1) The approximate hemispherical dichotomy, i.e. the profound asymmetry in Martian topography expressed by the dichotomy between the northern, lightly cratered and thus presumably younger, lowlands and the southern, heavily cratered (presumably older) highlands. 2) The Tharsis Rise, an elevated domal structure in the wetern hemisphere of Mars with a scale of about 3000 km, is composed of relatively young volcanics, in contrast with the presumably significantly greater age of the rise. The region includes three immense shield volcanoes, Arsia, Pavonis, and Ascraeus Montes, in a linear chain extending across the Tharsis uplift. Not far away is Olympus Mons, the largest shield volcano in the solar system, more than 25 km high and 700 km across the base.

O Mars gravity field model: we use the 75th degree and order "MGS75D" harmonic solution of Yuan et al. (2001). The model is illustrated in Figure 2a, in the form of a map of "free air" gravity anomalies, and in Figure 2b, as a map of geoid (or areoid) undulations computed with respect to a reference ellipsoid with an inverse flattening of 196.9, mean equatorial radius of 3397km, gravitational constant of 42828.358 km3s-2, and rotational rate of 7.0882181x10-5rads-1.

The short-wavelength gravity features are better represented in the free air gravity map. The largest free-air gravity anomaly on Mars is over Olympus Mons, exceeding 2800 mgal. The large gravity amplitudes and negative gravity rings surrounding all four of the large Tharsis volcanoes suggest flexural support with a thick elastic lithosphere, and little compensation. The map also reveals several areas with "mascon" (mass concentrations, presumably uncompensated burried loads) anomalies, caracterized by a central gravity high over a topography low, in association with a negative annular gravity anomaly, again suggesting flexural response of the the lithosphere. The largest mascon is associated with the Isidis impact crater. The northern hemisphere also includes the large mascon anomaly in the Utopia Planitia basin, and two large positive anomalies over the north polar regions, with no obvious correlation with topography. The southern hemisphere boasts two lower amplitude mascon gravity signatures, one associated with the western Argyre impact basin, and the other (smallest) with the deep Hellas basin in the east.

The global areoid displays the long wavelength features of the MGS75D model. The major geoid highs are centered at the volcanic regions of Olympus Mons and Tharsis Montes in the western hemisphere, and at Isidis and Utopia Planitiae in the eastern hemisphere (with surrounding areoid lows).

O Mars tectonic features: we use global maps of the distribution of grabens, fault scarps, and wrinkle ridges by Scott and Tanaka (1986), Greeley and Guest (1987), and Tanaka and Scott (1987), as used by Banerdt et al. (1992), as well as features seen in MGS data as used by Banerdt and Golombeck (2000).

Large scale tectonic features recognized in Mars surface imaging data include both extensional and compressional structures such as:
1) nearly ubiquitous, globally distributed wrinkle ridges, with a presumably compressional origin (Chicarro et al., 1985). Such ridges occur more commonly throughout ancient terrain, whereas in volcanic plains the distribution is highly uneven.

It has been suggested that ridge formation may have been concentrated in a relatively early state in Martian evolution.
2) Broad scale tectonic deformation confined to a more regional scale namely, for a large part, features in and near the Tharsis area. Tectonic features in the Tharsis area include a major system of graben (rifts) radiating from the center of Tharsis and spanning a region more than 8000 km across (i.e., found in and around the rise). These radial graben systems have generally been associated with concentric extensional stresses. The complex Tharsis rise region is also ringed by tly concentric wrinkle ridges that formed over 2000 km from the center of the rise. The examination of crosscutting relations between ridges and graben support the view that most ridge formation in the Tharsis region was restricted to an early time period (Watters and Maxwell, 1983).

III. MODELING METHOD AND RESULTS

1. Crustal and Lithospheric Thickness Study

The mean thickness of the crust and lithosphere for Mars provide two important constraints on surface stress models, support mechanisms for surface topography, and the tectonic, volcanic, and thermal evolution of the planet.

Indeed, the mean thickness of the Martian crust will have important imlications for the internal structure of Mars, the amount of crustal production, and the thermal history of the planet. This mean crustal thickness specifies the degree of fractionation of the interior, which in turn specifies the fraction of heat producing elements that reside in the crust (e.g., Turcotte et al., 2000), as discussed in section IV below.

The bending response of a thin elastic plate is governed by the flexural parameter (or wavelength) alpha, which is a function of shell and substrate densities, surface gravity, the radius of the planet, elastic parameters, and the thickness of the elastic plate (e.g., Banerdt et al., 1992). For loads with wavelengths much less than alpha, support will come essentially from bending (flexural) stresses. Loads with longer wavelengths will be supported via buoyancy (as in isostatic compensation) and/or membrane stresses (or "arch support", particularly important for small planetary bodies such as Mars and the Moon). Since the strongest dependence is on L and densities and elastic parameters can be estimated reasonably well, to a first approximation, the elastic lithosphere can be characterized by its thickness alone.

O Degree of compensation

Several studies, including work using pre-MGS data (e.g., Phillips and Saunders, 1975; Esposito et al., 1992) as well as work using MGS data (Smith et al., 1999b; Turcotte et al., 2000; Yuan et al., 2001), have suggested that a non-negligible portion of the Martian surface is substantially isostatically compensated. This concerns several regions in the southern hemisphere (including Hellas), and a few areas in the north.

For short wavelengths, topography is essentially uncompensated and correlates with the corresponding local gravity anomaly (Delta_g^u) through the Bouguer gravity formula. Correlations between gravity and topography can be used to determine the degree of compensation of surface loads.

In order to conduct a quantitative study of the extent of isostatic compensation, at the regional level, on Mars, we used the spherical harmonic models for Mars' geopotential and topography to obtain, within a 16degx16deg data window sliding on the Venus surface, 2degx2deg mean values of observed "free air" gravity anomaly (Delta_g), as well as (Delta_g^u) defined above. The regional degree of compensation for a given window position is defined as the slope of the best fit regression line for the [(Delta_g^u), -BA = (Delta_g^u) - Delta_g] data set, where BA is the Bouguer gravity anomaly. Results are shown in Figure ... which shows regional degrees of compensation for Mars. We find that, with the exception of the Tharsis area and lowland areas with subsurface loads, the surface of Mars is substantially isostatically compensated, with an average degree of compensation of more than 70%. As a note of interest, the Hellas basin is nearly fully compensated (at 86%). The lowest values are obtained for the Tharsis volcanoes and Elysium, indicating that they are essentially uncompensated. Lowland basins such as Utopia and mascon areas such as Isidis show up with values of compensation significantly in excess of 100%. This "overcompensation" (or "superisostatic state") is a characteristic signature for low areas with uncompensated loads burried under the surface (i.e., "bottom loads").

O Airy-Heiskanen isostasy

Taking isostasy as a working hypothesis, we performed an Airy isostasy (compensation through low density roots, with lateral variations in crustal thickness) study for Mars. Our goal here was to : 1) use the MGS data to examine the physical validity of the Airy compensation model on a regional basis, for the entire surface of Mars, and 2) for those areas where Airy isostasy is a viable support mechanism, derive a mean, zero-elevation (reference, or background) crustal thickness.

As seen above, at long wavelengths topography can be essentially compensated. In regions where isostasy prevails, correlations of geoid anomalies with topography variations are the preferred method to obtain information on the mechanism of compensation and determine the reference thickness of the crust (Ockendon and Turcotte, 1977; Haxby and Turcotte, 1978]. For Airy theoretical correlations, geoid anomaly N is related to topography variation h as:

where H is the zero-elevation (h=0) crustal thickness.

The map of regional, zero-elevation crustal thickness shown in Figure ... was produced using a forward modeling approach, with spatial domain Geoid-Topography Ratio (GTR) techniques [Kucinskas and Turcotte, 1994; Kucinskas et al., 1996] and the MGS data derived Mars gravity and topography models. We assumed densities of 2900 kg m-3 for the crust, and 3500 kg m-3 for the mantle. Taking isostasy as a working hypothesis, for each fixed position of a 960x960 km (16 degree x 16 degree) data window, sliding over the Martian surface, mean values of the spherical harmonic-derived geoid anomaly (N) and topography variations (h) are compared, in the least squares sense and in the spatial domain, with theoretical Airy correlations of N and h. This comparison results in a best fit value of the reference crustal thickness H for the region within the window. In computing regional GTRs, topography and geoid were gridded on an equal-area grid to avoid biasing the results as the poles are approached. This was accomplished following Kucinskas et al. [1996] using Euler angle rotations.

Examining Figure ... one can see that there are a number of areas on the planet where the Airy correlation does not work, i.e., where the Airy solution is not physically meaningfull (the value of H "blows up"). Those regions appear in the map either in blue (within the white, negative H contour lines), or in red (excessively large, positive values of H). Indeed, when the gravity data include all Martian mascons, the GTR modeling results yield large, negative compensation depths for lowland impact basins with large mascon gravity highs (for example, Utopia). What we are seeing there is the result of an excess, uncompensated burried mass over a topography low. Another large area where the Airy isostasy solution is inadequate is the Tharsis uplift region. The Tharsis structure is only weakly compensated and seems supported essentially by a combination of flexural and membrane stresses [Willemann and Turcotte, 1982; Banerdt and Golombeck, 2000; Turcotte et al., 2000, 2001; Kucinskas et al., 2001a]. However, the map also reveals several areas on Mars where the Airy model correlations yield plausible values for the regional, reference crustal thickness. These correspond to the green zones in Figure ... and are located predominantly in the southern hemisphere (including Hellas), but also in the northern regions. An analysis of the regional reference thickness results for those regions where Airy isostasy seems viable, yields a mean, reference crustal thickness of approximately 100 km.

O Elastic lithosphere thickness

Correlations between gravity and topography can also be used to estimate the thickness of the elastic lithosphere on Mars, taking into account the rigidity of the elastic shell of the planet as well as elastic lithosphere bending (Turcotte et al., 2001).

Following Turcotte et al. (1981), and Willemann and Turcotte (1981), and given our estimate of the mean, reference crustal thickness H, we compared, in the spectral domain, predicted dependence of the ratios of gravitational potential to topography on degree l for Mars for several values of the thickness of the martian elastic lithosphere, to the ratios of the observed variance spectra calculated from the observed topography and gravity spherical harmonic coefficients. From this comparison, we infer a mean, global elastic lithosphere thickness L for Mars of about 135 km.

2. Lithospheric Stress Modeling.

We have also investigated the implications for the thicker crust and lithosphere implied by this study in terms of the state of stress in the lithosphere, using the method of <italic>Banerdt et al.</italic> (1992; 2000). The method involves calculating the vertical deflection and internal density variations required to satisfy the gravity and topography for a given thickness of crust and elastic lithosphere. From the deflection, the state of stress and strain can be derived and compared with observed tectonic structures (e.g., Scott and Tanaka, 1986; Greeley and Guest, 1987; Banerdt et al., 1992). This method utilizes an analytic spherical deformation code based on a derivation of elastic thin shell theory by Vlasov (1964). Topography and gravity (represented as a set of spherical harmonic coefficients) are boundary conditions, and it incorporates a full thin shell treatment with horizontal gradient loads and both bending and membrane stresses. It includes both top- and bottom-loading; lithospheric deflection and a laterally varying crustal thickness (applied at the bottom of the crust) are dependent variables which are determined through the system of shell equations. Once the deflection is known, stress and strain are determined uniquely by the displacement field.
For these calculations, we assume a lithosphere thickness of 135 km, a mean crustal thickness of 100 km, a topography density of 2900 kg/m3, and a density contrast of 600 kg/m3.

We first calculated the crustal thickness for Mars assuming a mean thickness of 100 km, as derived from the analysis in the previous sections (Figure ...). This calculation assumes that all gravity anomalies are due to crustal thickness variations alone (Airy isostasy), with a uniform density assumed for both the crust (2900 kg/m3) and mantle (3500 kg/m3). Although the mean thickness is twice that assumed by <italic>Zuber et al.</italic> (2000), the variations in thickness are similar.

We find vertical deflections of the lithosphere ranging from about 5 km of uplift in the region ringing Tharsis, to greater than 10 km of depression beneath the major volcanoes and Utopia (Figure ...). The Tharsis plateau itself shows downward deflection of about 8 km, exclusive of the Tharsis Montes. We note that there is no appreciable lithospheric deflection associated with the dichotomy boundary. These deflections are somewhat smaller than those reported by Banerdt and Golombek (2000), consistent with the thinner lithosphere (100 km) assumed in that study. The computed stresses for this model (Figure ...) are broadly consistent with the tectonic patterns mapped by Scott and Tanaka (1986) and Greeley and Guest (1987). Extensional stresses in the western hemisphere are concentric to Tharsis, and show concentrations in regions with observed extensional tectonics (Tempe, Coprates, Thaumasia, Sirenum, Alba); in the eastern hemisphere they are consistent with the east-west structures in Elysium and the concentric grabens around Isidis. Compressional stress directions have the correct orientation to produce the wrinkle ridges in Lunae Planum, Solis Planum, and Tempe Terra, and are consistent with the concentric features see in the MOLA topography of Utopia.

We conclude that the relatively thick values for the crust and elastic lithosphere indicated by our geoid-topography analyses are mechanically consistent with the observed geology of Mars.

IV. GEOPHYSICAL IMPLICATIONS

We now examine the geophysical constraints on the mean, reference crustal thickness as well as the implications of a thick crust for Mars' structure and thermal history.

For a terrestrial planet, the maximum basaltic component that you can extract (via partial melt) from the fertile mantle into the crust (i.e., to form crust) is about 20% [Turcotte and Schubert, 1982]. Then, from mass balance, following Schubert et al. [1992], this yields a corresponding maximum thickness of crust that can be formed on Mars of approximately 300 km. Also, it can be noted that the thick, mean crust derived in this work is in good agreement with predictions of models of the Martian interior based on the geochemistry of SNC meteorites [Spohn et al., 1998].

The value of 100 km derived for the mean, reference crustal thickness in this work is significantly greater than the assumed 50 km mean crustal thickness of Zuber et al. (2000), which was adopted on the basis of viscous relaxation arguments. Indeed, these authors argued that if the Martian crust is more than 50 km thick on average, the weak lower crust would relax away the observed longitudinal structure on time scales shorter than 10^8 years. However, this does not take into account the possibility that Mars is a highly differentiated planet, where a large (if not all) part of the radiogenic heat producing elements (HPE) have been fractionated (removed) into the upper crust.

It is noteworthy that the extraction of HPE into the Martian crust affects sigificantly the thermal evolution of the planet. Calculations by Schubert et al. [1992] have shown that in this situation most of the crustal growth occurs early in the evolution of Mars (i.e., within a short time after the end of accretion).
Without crustal recycling, magmatism could have created a thick crust early in Mars' evolution, with a substantial fraction of radiogenic HPE fractionated into the crust, resulting in a cool, highly differentiated interior, an increase in lithosphere thickness, and the decay of tectonic and volcanic activity. Then, these authors further argue, assuming that the concentration of

crustal HPE on Mars decreases exponentially with depth, as is the case for continents on Earth [Turcotte and Schubert, 1982], results in a colder, high viscosity lower crust which could then be maintained against relaxation for a significant part of Martian history.

With the extraction of the HPE from the mantle into the upper crust, the thermal lithosphere will become considerably thicker. In fact, if the whole planet was molten initially, simple parametrized convection calculations show that the cooling off phase will take place quickly and yield a strong (thick) enough lithosphere to support a thick, rapidly formed crust. As an example, for a 100 km mean crust on Mars, these planetary evolution calculations [Schubert et al., 1992] show that the conductive thermal lithosphere will be approximately 200 km thick after only 1 billion years.
Thus, with a 100 km mean, reference crust, cooling has indeed been fast enough for isostasy to maintain variations in crustal thickness, and, for example, such features as the deep Hellas basin.